

N96-13722

*Airborne Astronomy Symposium on the Galactic Ecosystem
ASP Conference Series, Vol. 73, 1995
M.R. Haas, J.A. Davidson, and E.F. Erickson (eds.)*

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SOFIA: The Future of Airborne Astronomy

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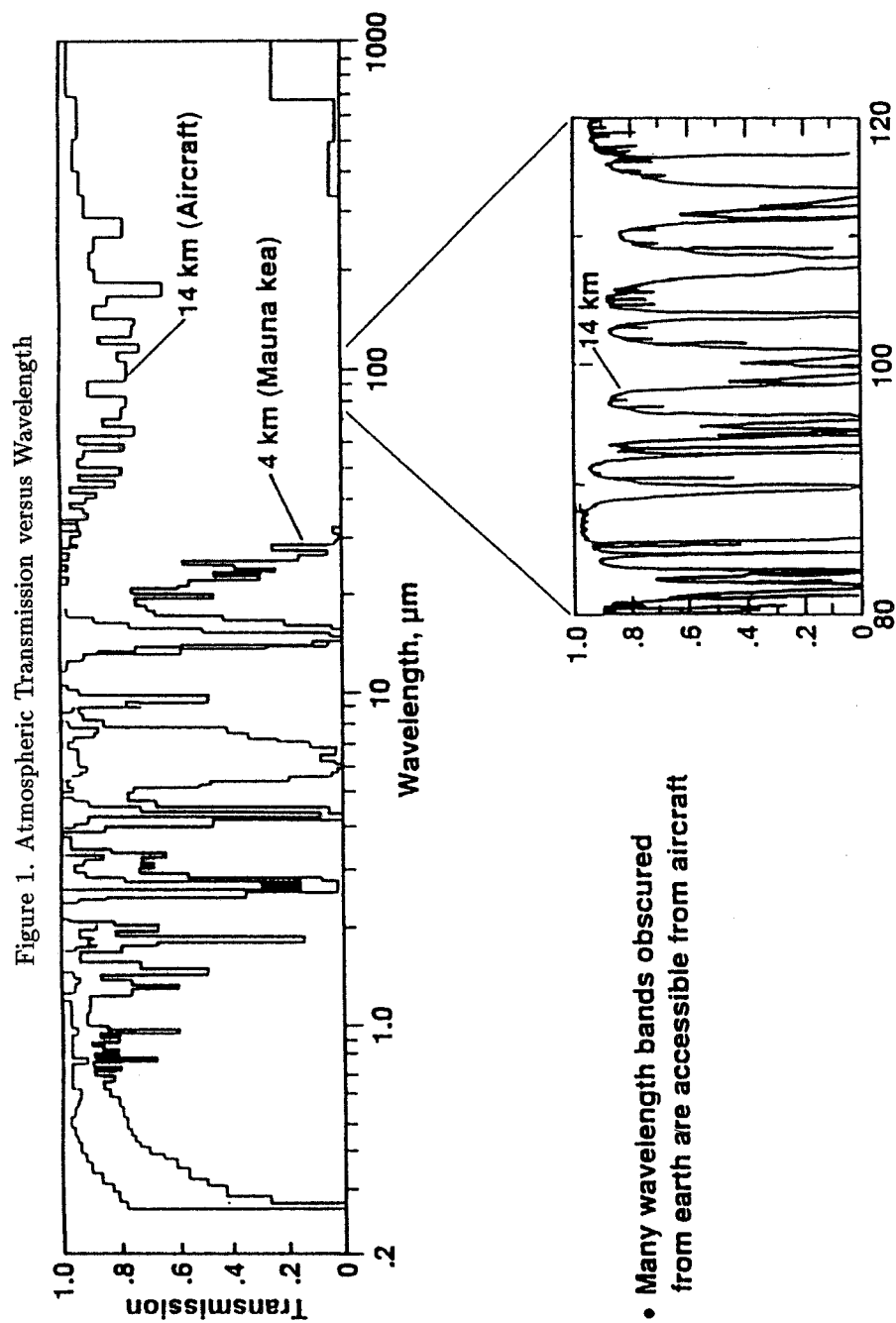
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Abstract. For the past 20 years, the 91 cm telescope in NASA's Kuiper Airborne Observatory (KAO) has enabled scientists to observe infrared sources which are obscured by the earth's atmosphere at ground-based sites, and to observe transient astronomical events from anywhere in the world. To augment this capability, the United States and German Space Agencies (NASA and DARA) are collaborating in plans to replace the KAO with a 2.5 meter telescope installed in a Boeing 747 aircraft: SOFIA - The Stratospheric Observatory for Infrared Astronomy. SOFIA's large aperture, wide wavelength coverage, mobility, accessibility, and sophisticated instruments will permit a broad range of scientific studies, some of which are described here. Its unique features complement the capabilities of other future space missions. In addition, SOFIA has important potential as a stimulus for development of new technology and as a national resource for education of K-12 teachers. If started in 1996, SOFIA will be flying in the year 2000.

1. Airborne Astronomy - the Legacy

For nearly three decades astronomers have been making infrared observations from aircraft based at NASA's Ames Research Center in California. In 1965 Gerard Kuiper used the NASA Convair 990 to show that the clouds of Venus were nearly devoid of water, demonstrating the advantages of airborne observations in the near infrared. In 1968 the Ames Learjet was used by Frank Low to measure far infrared luminosities of Jupiter and Galactic nebulae. In 1974 the Kuiper Airborne Observatory (KAO) started its now 20 year career as a national facility for astronomy. Its users have produced ~ 1000 refereed publications, and ~ 50 Ph.D. theses for students at U.S. and foreign universities; it also supports kindergarten through high school teacher outreach programs. A good review of the KAO program and its contributions to science, education, and technology is given by Larson (1994).

Most infrared radiation from astronomical objects which never reaches the ground is detectable from the lower stratosphere. This fact is the principal justification for an airborne telescope. Figure 1 plots computed atmospheric transmission (Traub & Stier 1976) as a function of wavelength for aircraft (14 km) and mountain-top (4 km) altitudes. The absorption is largely due



to water vapor, with significant contributions from carbon dioxide and ozone in some wavelength bands. The model assumes overhead water quantities of $2.3\ \mu\text{m}$ for the aircraft and 1.2 millimeters for the ground-based telescope, and a zenith angle of 60 degrees. From 14 km, the broadband atmospheric transmission is adequate ($\geq 70\%$) for photometric observations at most infrared wavelengths, but the emissivity limits detector sensitivity due to the fluctuations in the arrival rate of the photons from the sky. A number of the water lines in the far infrared are still saturated at aircraft altitudes, as shown in the lower panel. Between these lines the transmission can exceed 95%, the emissivity is correspondingly low, and so high resolution spectrometers can achieve sensitivity limited principally by the emission of the telescope.

Despite the numerous saturated atmospheric lines at aircraft altitudes, most important astronomical spectral features can be measured from an airborne observatory. To demonstrate this, we list in Table 1 the spectral features originating in the interstellar medium (ISM) which have been observed from the KAO. These features characterize important phases of material in the ISM: molecules, neutral and ionized atoms, and solids, as discussed in Section 3. A sample of the research done from the KAO is presented in this volume.

The extensive scientific and technical heritage of the airborne program, and particularly our experience with the KAO, provides a solid basis to project the performance and the design of the next generation airborne observatory – SOFIA.

2. Characteristics and Performance

SOFIA's characteristics are summarized in Table 2. The large aperture and wavelength range, routine accessibility to most infrared wavelengths, and mobility are unique features of the observatory (Caroff 1994). Relative to the KAO, SOFIA will be roughly ten times more sensitive for compact sources, enabling observations of fainter objects and measurements at higher spectral resolution. Also, it will have three times the angular resolving power for wavelengths greater than about $10\ \mu\text{m}$, permitting more detailed imaging throughout the far infrared.

The anticipated performance of SOFIA is indicated as a function of wavelength in Figures 2 through 5. Figure 2 shows the expected image quality, which is limited by seeing from the air flow over the telescope cavity at visible and near infrared wavelengths, and by diffraction at long wavelengths. The specified performance of the optical system limits the image quality in the $\sim 4\text{--}10$ micron range. Figure 3 shows the anticipated photometric sensitivity per pixel, which is simply scaled from the performance achieved on the KAO. Here "PSC" and "FSC" refer to the IRAS Point Source and Faint Source Catalogues, respectively. We see that SOFIA would be able to observe any of the compact infrared sources in these catalogues. High resolution spectrometers are expected to be available for most of the wavelength range of SOFIA, as indicated in Figure 4. Interstellar lines are typically broadened to a km/sec or more, whereas higher resolving power can be useful for study of solar system objects. Spectroscopic sensitivity, shown in Figure 5, corresponds to the spectral resolving power shown in Figure 4. Narrow lines emitting more than 0.1% of the total continuum emission from the IRAS sources should be detectable. The important cooling lines of neutral

Table 1
INTERSTELLAR SPECTRAL FEATURES DETECTED FROM THE KUIPER AIRBORNE OBSERVATORY

DUST GRAINS		ATOMS		MOLECULES	
λ (μm)	SPECIES	λ (μm)	SPECIES	λ (μm)	SPECIES
2.95?, 6.3, 7.1 a	NH ₃ Ice	1.88, 2.62, 2.67, 2.76, 4.65,	H I	1.4, 1.8 a	C ₂
5.2, 5.6, 6.2, 6.9, 7.6, 7.8	PAH	5.91, 6.6, 7.5, 52.5		2.0, 2.6, 7.5 a	C ₂ H ₂
5.5 a	HCO in Ice	3.1, 7.5	Ni I	2.3, 4.6, 77, 84, 87, 97, 100, 103,	CO
6.0, 62, 45 a/e	H ₂ O Ice	4.5	Mg IV, Ar VI (?)	119, 124, 153, 163, 174,	
6.8 a	Hydrocarbon	5.6	Mg V	186, 200, 289, 302, 650	
19.0 a/e	silicate	6.6	Ni II	2.9 a	C ₂ H
24-30+	MgS (?)	6.98	Ar II	3.0, 3.5, 7.5 a	HCN
45, 62 a/e	H ₂ O	7.63	Ne VI	5.0 a	C ₃
		8.99, 21.8	Ar III	8.5	Si O
		17.9, 26.0	Fe II	17.0	H ₂
		18.7, 33.4	S III	53.4, 84.4, 84.6, 119.3,	OH
		22.9	Fe III	119.5, 149, 163.1, 164.4, 202 a/e	
		24.3	Ne V	154, 308	¹³ CO
		25.2	S I	120.0, 120.2 a/e	¹⁸ OH
		25.9	O IV	125, 166, 524	NH ₃
		34.8	Si II	149.1, 149.4, 203	CH
		36.0	Ne III	479	HCl
		51.8, 88.4	O III	790, 1600	H ₂ O
		57.3	N III	805	H ₂ D ⁺
		63.2, 146	O I		
		121.9, 205	N II		
		158	C II		
		158	¹³ C II		
		370, 609	C I		

Almost all of these features were first detected from NASA's airborne observatories, and cannot be studied from ground-based sites. Features seen in absorption are indicated with "a", and seen in both emission and absorption with "a/e". Whereas the dust features typically originate in regions cooler than a few hundred degrees Kelvin, the various gaseous lines originate in regions ranging in temperature from $\sim 10^5$ K down to ~ 10 K. Thus these infrared spectral features characterize material in all phases of the interstellar medium: solid particles, molecules, neutral atoms, and ionized atoms.

Table 2
Summary of Basic SOFIA Characteristics

In-flight access to focal plane instruments – continuous
Vehicle – Boeing 747
Operating altitudes – 41,000 to 45,000 feet
Aircraft-limited duration at or above 41,000 feet \gtrsim 5 hours
Nominal flight duration (crew-limited) – 7.5 hours
Research flights per year – \sim 160
Number of PI teams flown per year – \sim 60
Number of focal plane instruments flown per year – \sim 15
Frequency of science proposal peer review – annual
Stabilized telescope system weight – \sim 8,000 kg
Effective primary mirror diameter – \sim 2.5 meters
Wavelength range – 0.3 to 1600 microns
Telescope configuration – Nasmyth
Design f/ ratio – \sim 20
Design plate scale – 4 arcseconds/mm
Unvignetted field of view – 8 arcminutes
Telescope optical image quality \lesssim 1 arcseconds
Shear layer seeing – \sim 3 arcseconds (0.3 to \sim 5 microns)
Diffraction-limited at wavelengths – \gtrsim 10 microns
RMS pointing stability – \lesssim 0.2 arcseconds
Telescope emissivity – \lesssim 15%
Telescope elevation range – 20 to 60 degrees
Nominal operating optics temperature – \sim 250K

oxygen at $63\ \mu\text{m}$ and C^+ at $158\ \mu\text{m}$ from photodissociation regions are typically this strong relative to the continuum. Shocked interstellar gas will produce a higher line to continuum ratio.

3. Science

The infrared spectral regime encompasses a multitude of rich and varied physical processes and is uniquely suited for the study of cosmic birth on all scales. SOFIA will be an essential tool in many of these studies. Among the primary goals of SOFIA scientists is a detailed and comprehensive study of the processes which lead from cold clouds in the Interstellar Medium (ISM), through the formation and evolution of stars and planetary systems, to the eventual return of processed material to the ISM. Astronomers will also use SOFIA's superior spatial and spectral resolution to examine the dust and gas in the vicinity of our Galactic Center, to search for the signature of a massive black hole which may be the central powerhouse of the Galaxy, and to examine the origin of the massive stars observed there. On still larger scales, SOFIA will provide new understanding of global star formation in galaxies and the origin of the extraordinary luminosities of some infrared-emitting galaxies discovered by IRAS. In addition, the unique mobility of an airborne observatory

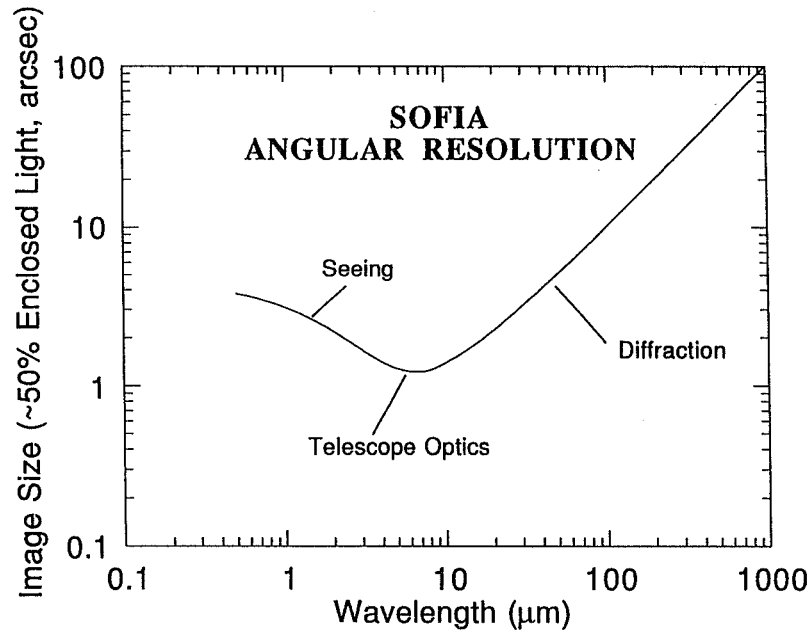


Figure 2. Anticipated image quality versus wavelength.

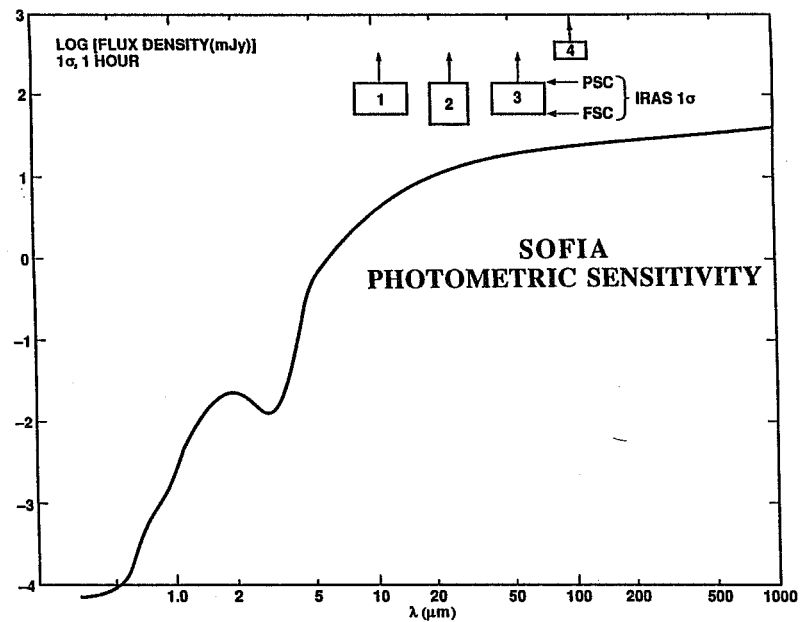


Figure 3. Anticipated photometric sensitivity versus wavelength.

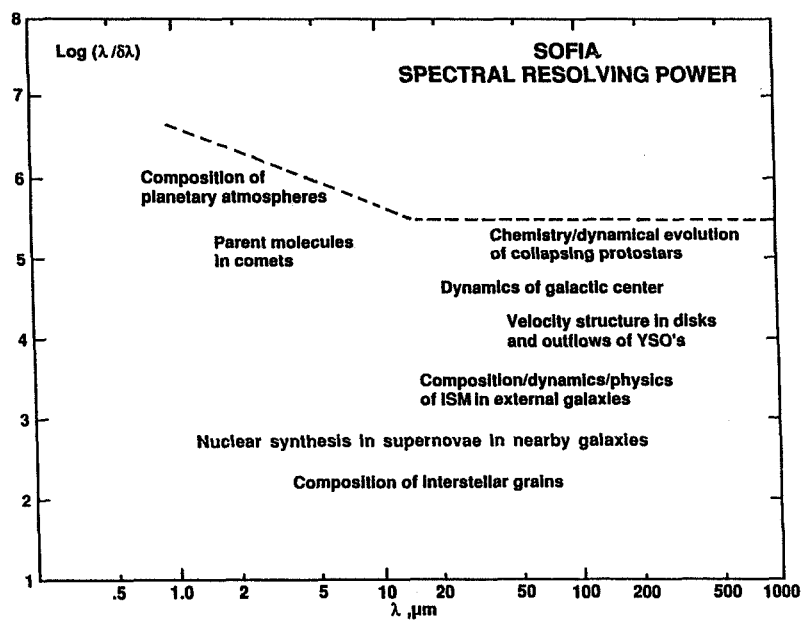


Figure 4. Anticipated spectral resolving power versus wavelength.

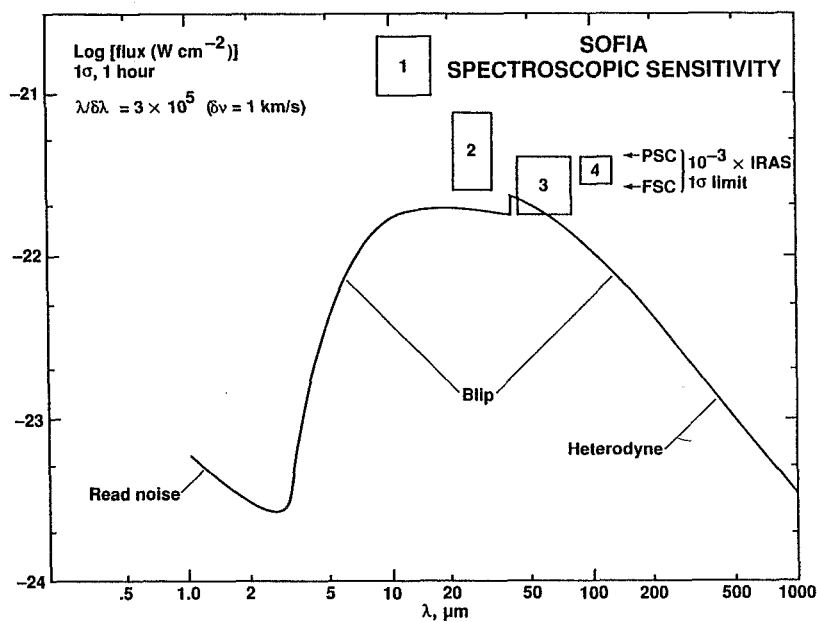


Figure 5. Anticipated spectroscopic sensitivity versus wavelength.

allows effective response to a number of highly localized and sometimes quite transient phenomena, such as solar eclipses, comets, novae, supernovae, and stellar occultations by solar system bodies. We discuss a number of specific examples below:

(i) The Interstellar Medium

All galaxies are permeated by an Interstellar Medium, but with properties which may vary greatly from galaxy to galaxy. Fundamental components of the ISM – solids, molecular gas, neutral atomic gas, and ionized gas – are characterized by infrared, far-infrared, or sub-millimeter emission and this emission generally dominates the cooling of the gas and dust. Observations of the ISM are critical to the study of the cycle of gestation, birth, evolution, and death of stars for the following reasons:

(a) The composition of the ISM determines the chemical makeup of the objects which form from it; (b) The structure, energy balance, and physical state of the ISM in a particular region determine the nature of subsequent evolution, for example in the formation of high mass versus low mass stars; (c) The structure and dynamics of the ISM, in turn, are strongly influenced by young stars which interact with the ISM via wind-driven shocks and ultraviolet radiation; and (d) Interesting phenomena are often embedded in dense, dusty regions of the ISM and can only be observed indirectly through the interaction of the source with the ISM. Therefore an understanding of the properties of the ISM is essential to interpret observations of the embedded sources correctly.

From SOFIA, astronomers would map the total and polarized thermal continuum from cool dust in molecular clouds with high spatial resolution, as well as the corresponding power radiated in atomic fine structure and rotational molecular lines. These measurements provide estimates of the density, luminosity, temperature, chemical and dust grain makeup, magnetic fields, dynamics, and detailed morphology of these regions.

Carbon chemistry is the basis of life as we know it, and has its beginnings in the ISM. Carbon emission lines also provide a large percentage of gas cooling in the ISM, thus altering the ISM environment and subsequent chemical evolution. Spectroscopy will yield particularly significant results on carbon chemistry in clouds, via

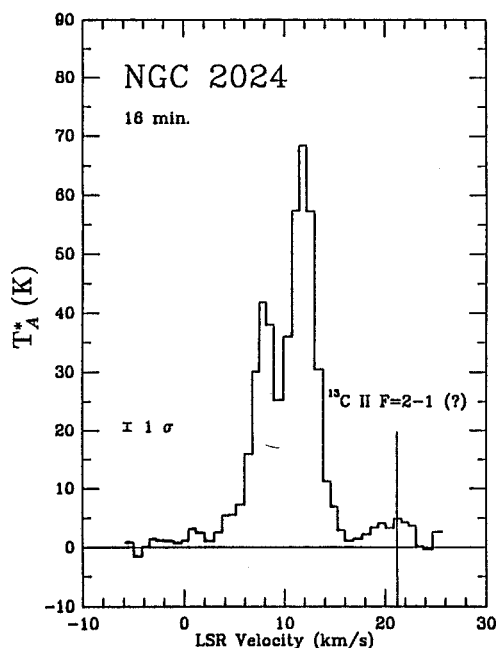


Figure 6. Velocity resolved spectrum of C^+ at $158 \mu\text{m}$.

the 158 μm C^+ line, the 370 and 609 μm C lines, a host of FIR and submm rotational CO lines, and numerous near-infrared absorption lines of basic organic molecules such as CH_4 , C_2H_2 , and C_2H_4 . As an example, Figure 6 shows a KAO measurement of the C^+ line from NGC 2024, a molecular cloud/ionized gas complex, obtained with a velocity resolution $\lesssim 1$ km/s. Line observations at such high spectral resolution provide information on systematic and turbulent motions within a cloud.

(ii) Star Formation

The ubiquitous associations of young stars with dark clouds clearly tells us that star formation occurs in dense regions of the ISM. The star formation process is not well understood. For example, it is not known why or when a region of a cloud will start to collapse. In order to form a one solar mass star, the collapse must extend to a radius of about 10^{17} cm in a quasi-stable dense clump in an interstellar cloud. This distance would correspond to just under an arcminute on the sky if we were observing the collapse in the nearest star formation region, the Taurus cloud, which is 160 pc away. SOFIA's ten arcsecond resolution at 100 μm will readily resolve this infall region. The radiation from the star formation region in its early stages of evolution would be dominated by an accretion shock around the small protostar, and would peak in the far-infrared due to the large dust opacity in the surrounding cloud.

A number of IRAS point sources have been studied from the KAO and have been shown to be visibly obscured young stellar objects (YSO's). The improved spatial resolution of the KAO over IRAS has allowed determination of the mean densities and temperatures of the infall regions and star formation environments. SOFIA's ten times better sensitivity and three times higher spatial resolution will enable us to make detailed images of the infall regions and their envelopes. SOFIA will, for the first time, detect the dominant cooling transitions of the infalling gas and directly measure the mass infall rate and velocity structure by high spectral resolution observations of the far infrared CO and O I emission lines. High spatial resolution observations of the dust continuum will probe the density structure of the circumstellar gas down to scales of 100–1000 AU. The ambient molecular core is expected to have a density $\propto r^{-2}$, while the infall region theoretically has a density $\propto r^{-3/2}$. The infalling gas and dust generally have sufficient angular momentum to impact an opaque (~ 100 AU) accretion disk which orbits and feeds the growing star. SOFIA will measure infrared OH spectral lines generated in the accretion shock and thereby determine the mass accretion rate, the location on the disk where the infalling gas and dust mainly strike, and the angular momentum of the impacting material. In summary, SOFIA will revolutionize our understanding of the collapse phase of star formation.

In massive clouds, stars often form in clusters where we currently cannot separate the individual YSO's. Many of these could be isolated in the beam of SOFIA so that, for example, their individual luminosities, masses, and motions relative to one another could be determined. The shape and color of the continuum spectra reveal the evolutionary state of the system. These observations will greatly help us understand the process of fragmentation of large clouds to form star clusters.

(iii) Bipolar Outflows

Since the 1980's, observations have shown that many embedded YSO's are associated with powerful bipolar outflows. These outflows may collide with the circumstellar gas and cause accretion to cease. In this way, they may help determine the final mass of the star. Several theories have arisen to explain the origin of these protostellar winds; they share a common idea that magnetic fields rotating with the protostar or the disk fling trace ions from the inner part of the disk outwards and these ions drag neutral gas along. With SOFIA we can look for evidence of simultaneous inflow along the equatorial plane with outflow along the poles, determine the stage in the evolution of a star when the outflows "turn on", trace the shock interaction of the outflow with the circumstellar gas, and measure the mass-loss rates in the protostellar winds with good fidelity by observing the luminosities in shock-excited O, S, and Si II fine structure lines. FIR polarimetry from SOFIA of the infall regions will show, in the more luminous cases, the association between magnetic fields and outflows.

(iv) Circumstellar Disks

Circumstellar disks have been observed around T Tauri stars, which are thought to be very young stars with masses comparable to that of our Sun. These stars and their disks are formed in obscuring parent clouds. It is thought that the outflows mentioned above could eventually halt the disk accretion. The outflows could also dissipate the surrounding cloud, making the YSO's eventually visible as T Tauri stars. At a later evolutionary stage the disks will dissipate or form planets, and there will be considerable disk clearing. Theoretical models predict that OH emission produced by shock waves set up in the disks by accreting material should be detectable from SOFIA, and the OH line luminosities and profiles can be used to measure the mass accretion rate feeding the disk and the location on the disk where the infalling gas and dust mainly strike. Photometric submm and FIR observations help determine the mass of the disk, which is an essential quantity in understanding planet formation and how disk instabilities may cause the orbiting particles to spiral inwards and accrete onto the star. The disk mass and the accretion rate onto the disk determine the timescale for the formation of the disk; if this timescale is very short it may indicate that, on average, the disk feeds material onto the star as fast as infalling material feeds the disk. Observations of T Tauri stars have shown indirectly that circumstellar disks are generally not much more than 100 AU in diameter – comparable to the size of the solar system – or about 0.6 arcsec at 160 pc. However, HL Tau has been observed at millimeter wavelengths to have a dim 4000 AU (or 24 arcsecond) diameter disk, and FIR photometry from the KAO shows extended emission associated with several T Tauri stars, for example SVS 13. One theory posits that the extended disks are caused by ordered magnetic fields in the ambient cloud which channel the infalling material to an equatorial "pseudo-disk" that is not rotationally supported. The infalling gas then falls radially inward along the equator until it strikes the much smaller rotationally supported disks. Thus at an early stage of their evolution, these disks may be sufficiently extended and luminous to be imaged directly at FIR and submm wavelengths from SOFIA, which would be an exciting and extremely important input to theoretical understanding of low- and intermediate mass star formation.

At later stages of circumstellar disk evolution, when planets are forming or have formed, the disks are harder to see. However, there are ~ 50 candidates for evolved stars with disks which are on the order of 20 times closer to Earth than the nearest T Tauri star, and at their distances 100 AU in the disk corresponds to 10 – 15 arcsec on the sky. The spatial resolving power and sensitivity of SOFIA will allow direct imaging of the structure of a number of these disks for the first time in the FIR. For example, Beta Pictoris (β Pic) is a main-sequence star that is 17 pc away from Earth with an infrared-luminous disk discovered by IRAS. The infrared disk diameter is ~ 2400 AU, or 140 arcseconds, with the bulk of the infrared flux coming from the central 30 arcseconds. The total IRAS 60 μm flux of the disk, when distributed into five arcsecond diameter pixels – the resolution of SOFIA at 60 μm – will require less than 30 minutes of integration on SOFIA for a signal to noise ratio of 10. It will be possible, therefore, to determine the disk temperature profile and morphology. Combining these results with the knowledge of the illuminating star, β Pic, will enable the properties of the dust in the disk to be studied, in particular the dust-grain size distribution. Figure 7 shows the visible β Pic system with the 5 arcsecond diameter, 60 μm SOFIA beam. The properties of the dust are important since it is probably from these particles that the cores of planets may eventually form, if not in the β Pic system, then in similar disks around other stars.



Figure 7. Optical photograph of the β Pic disk, with 60 μm SOFIA beam size superposed. The stellar image has been blocked with an occulter.

SOFIA can map spectroscopic features in the disk as well, for example the water ice feature at 48 microns and the polycyclic aromatic hydrocarbon (PAH) features at 5.2, 6.2 and 7.7 microns. Such features help to ascertain the composition of the dust and hence the nature of planets which may be forming at particular locations in the disk.

(v) Our Solar System

The initial composition of our pre-solar nebula is of great interest because it contained the building blocks of the planets and of life. SOFIA's ability to explore an early pre-planetary system environment through observations of nearby circumstellar disks was discussed in §(iv). SOFIA will also image, spectroscopically as well as photometrically, dense clumps in nearby dark clouds, in order to determine the composition of future pre-solar nebulae. However, to better understand the origin of our Solar System, studies of comets, planets, and satellites are essential.

Comets

Comets are aggregates of ice, dust, and organic solids that accumulated in the region of the solar nebula where the outermost planets formed, and as such they are the most accessible repositories of chemical remnants of the original interstellar material that spawned the solar nebula. Observations of many comets show that they are an eclectic sampling of different regions of the solar nebula; some show abundant reduced carbon, some show no carbon at all, some exhibit silicate minerals, and others show hydrocarbons and minerals in various proportions.

Spectroscopic studies of comets in the near infrared ($2-8\ \mu\text{m}$) with SOFIA can address questions of the chemistry and processing of carbon in the solar nebula through analyses of the reduced carbon (CH_3OH = methanol, and other organics) and oxidized carbon (CO_2 = carbon dioxide). Carbon dioxide in comets cannot be observed from the ground, but with a favorable Doppler shift, high-resolution spectroscopy from SOFIA will permit observations of this key molecule in the volatile carbon budget. Even though the discovery of organic material in the nuclear dust of Comet Halley was achieved from the ground looking at the C-H stretch feature near 3 microns, in order to determine the nature of the molecules producing this feature we must observe these species between 5 and $8\ \mu\text{m}$ where the C-O, C-C, and C-N stretch bands are found. Again these wavelengths cannot be observed from the ground, but are readily accessible to an airborne platform.

Similarly, water in comets cannot be detected from ground-based observatories, but as demonstrated by its discovery in Comet Halley from the KAO (Figure 8), water is readily measured at high spectral resolving power ($\sim 10^5$) from the lower stratosphere. The ortho-to-para ratio in the hydrogen in H_2O in comets (measurable at $2.75\ \mu\text{m}$), as well as the deuterium content of the water ($\text{HDO}/\text{H}_2\text{O}$), establishes the temperature of formation of the comets ($\sim 30\ \text{K}$ for Halley), as well as the local chemistry of the solar nebula at the comet formation site(s). A basic question about the local chemistry is whether the processing of water and the organics was controlled by kinetics or by ion-molecule reactions. The relevant observations can only be made from SOFIA, whose large aperture, long lifetime, and sensitive two-dimensional array spectrometers will make available many more comets than can be observed from the KAO.

Finally, SOFIA will have the sensitivity to study solid state features (such as water ice and olivine) in short period comets. These comets have orbits that extend to about 7 AU from the Sun, and therefore may contain material that has undergone considerable processing by solar radiation. Comparison of these materials with those seen in long period comets, which sample a more pristine environment, will be extremely interesting.

Planets and Satellites

A related fundamental question concerns the initial compositions of the volatiles incorporated into the giant planets and their satellites during formation, since these would imply certain conditions in the regions of the solar nebula where they formed. Two extreme models are that the outer planets and their satellites consisted of (a) water, methane, and ammonia (in order of decreasing abundance) or (b) carbon monoxide, water, and molecular nitrogen. In the

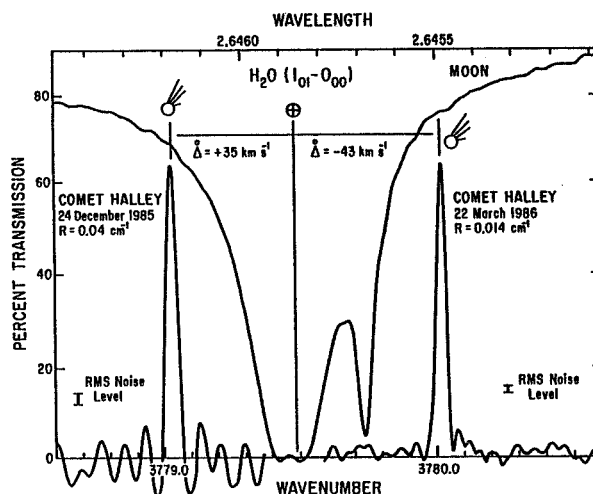


Figure 8. Spectra of water in Comet Halley and the moon taken from the KAO, which was scheduled to maximize the Doppler-shifted separation of the comet and telluric features. The spectral resolving power is $\sim 2 \times 10^5$.

currently accepted model, the giant planets consisted of composition (b), while in their satellites composition (a) dominated. Jupiter and Saturn might have converted the carbon monoxide to carbon dioxide and methane, and the nitrogen to ammonia, but Uranus and Neptune should have retained substantial amounts of their original composition. The satellites of the outer planets may retain surface spectral signatures of the primordial partitioning of these constituents. It is therefore important to determine the composition of the volatile-rich outer planet satellites and Pluto, the composition of their atmospheres (if any) and the nature of the surface-atmosphere interactions.

Better understanding of the atmospheres of the giant planets will further elucidate questions about the chemistry of the solar nebula. High resolution spectroscopy from near infrared to submillimeter wavelengths enabled by SOFIA will be especially suited to measurements of trace constituents in the atmospheres of the giant planets. Several trace gases on Jupiter (*e.g.*, GeH_4 and CO , present at the 10^{-8} levels of concentration with respect to H_2) have been found with the KAO in the $2 - 5 \mu\text{m}$ spectral region. The determination of a larger inventory of these constituents in Jupiter and the other giant planets from sub-millimeter spectra, and the computation of the vertical distribution profiles, will yield fundamental information on the photochemistry in the atmospheres of these planets. Some of the same photochemical processes occur in the atmospheres of the Earth and other terrestrial planets, thus allowing comparative studies of direct relevance to our own planet.

SOFIA's angular resolution will permit zonal resolution on a number of Solar System bodies. Imaging spectroscopy will reveal spatial variations of atmospheric, comatic, or surface constituents with a resolution of about 2 arcsec in the near infrared, increasing to 10 arcsec at 100 microns. The spatial resolution also reduces line broadening. On Mars (diameter 4800 km), 2 arcsec

corresponds to ~ 400 km, and on Jupiter (diameter 14300 km) to ~ 700 km. Spatially resolved spectra of Mars with SOFIA will give important information on the exchange of volatiles (CO_2 , and perhaps H_2O) between the polar caps and the temperate regions as the Martian seasons change, and will reveal the zonal and latitudinal distribution of the major and minor atmospheric constituents. SOFIA can resolve the Great Red Spot of Jupiter in the $2-8\ \mu\text{m}$ region where the chromophores, causing the still-unexplained color, may have their diagnostic spectral signatures.

In addition, much valuable research will be done from SOFIA on planetary bodies too small to be spatially resolved. For example, Pluto and Triton are two significant bodies in the outer Solar System, each composed of a mixture of rock and ice. Their tenuous atmospheres (of mostly nitrogen) appear to be in vapor pressure equilibrium with their surface ices. Both Triton and Pluto experience extreme seasonal cycles, and determining the interaction between their surfaces and atmospheres over these cycles is quite complex. Understanding this interaction requires simultaneous knowledge of several related parameters, such as the dimensions of the body, albedo distribution across the surface, temperature, surface composition, and atmospheric density. Significant variations in the parameters will occur during the lifetime of SOFIA. A unique contribution to this problem will be SOFIA's observations of stellar occultations by Pluto and Triton over the years, to determine the densities of their tenuous atmospheres at various points in their seasonal cycles. The same observations are vital in constraining the diameter of Pluto (Triton's diameter is already well known from spacecraft data). FIR photometric measurements from SOFIA can provide the color temperature and its variation with rotation and season for both bodies. In combination with optical photometry, these data will provide information on the albedo distribution and its time variation. Finally, low-resolution IR spectroscopy will provide new information on the composition of the surface ices.

Stellar occultations, which probe Solar System objects with a spatial resolution of only a few kilometers, are of course applicable to a variety of other problems. An airborne observatory is ideally suited to this powerful technique, since it permits the telescope to be optimally located and weather-free for a particular event. The value of deployment has been demonstrated by the KAO's history of occultation work, most dramatically by the discovery of the ring system around Uranus in 1977 (Figure 9).

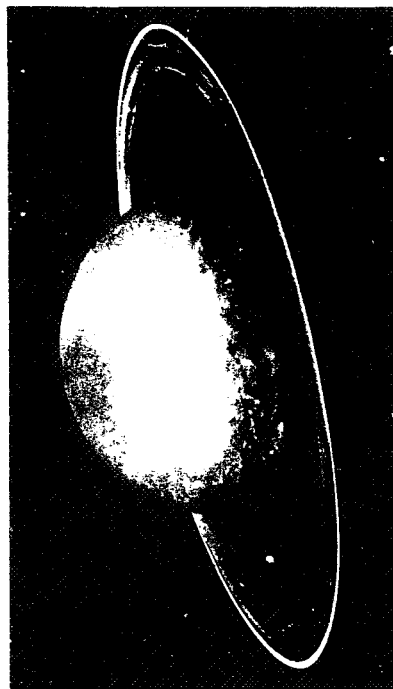


Figure 9. Artist's concept of the rings of Uranus discovered from the KAO.

SOFIA will be capable of observing many more occultations than the KAO, with greatly improved signal-to-noise, because of its increased aperture. Besides the studies of Triton and Pluto, SOFIA can obtain temperature, pressure, and number density profiles of the atmospheres of Uranus and Neptune, bodies for which no spacecraft entry probes are currently planned. SOFIA can also be used, in conjunction with ground-based information observations, to vastly improve our knowledge of Saturn's ring dynamics through observations of a series of ring occultations. From observations spanning several years, the orbits of the edges and narrow singlets in the ring system can be determined with much greater precision than has been possible with flyby spacecraft. Improved orbital information will lead to further understanding of the ages of the rings (whether they were formed with Saturn or more recently), the evolutionary processes in particle disks, and the internal structure of Saturn (from its gravitational harmonic coefficients).

As spacecraft are sent to Jupiter (Galileo), Saturn (Cassini), and to the small bodies of the Solar System (e.g., Clementine and NEAR), supporting observations from SOFIA will be of long-term importance. For example, the infrared spectrometer ($\sim 15 - 500 \mu\text{m}$) planned for Cassini has a spectral resolution of only 1 cm^{-1} , sufficient for detection of molecular lines in the far-infrared, but insufficient for observations of the intrinsic line profiles. Complementary high-resolution spectroscopy from SOFIA will establish the intrinsic line shapes to reveal physical conditions, in the atmospheres of Saturn and Titan, for example. Similarly, results obtained from SOFIA may help to define future space missions, as the KAO occultation results on Pluto have done for the Pluto Fast Flyby mission.

(vi) The Sun

The star that influences Earth the most is our Sun, not only through its radiation but through its solar wind as well. The solar wind originates in the chromosphere and corona, although the energy transport mechanism which heats the corona and drives the wind is not well understood. Oscillation of the solar atmosphere probably plays a role in this process, and pioneering FIR observations on the KAO, combined with ground-based sub-millimeter observations, have detected the oscillations at different depths in the solar atmosphere. Wavelength-dependent phase differences show the vertical transport of energy at the oscillation frequency. Far-infrared beam sizes from SOFIA will be well matched to the size of the oscillation cells, and will provide improved information on the strength of the oscillations and on the correlation between adjacent cells. This will yield significant insight into the energy transport mechanisms in the solar atmosphere.

(vii) Stellar Structure

In the last fifteen years, studies of multi-mode pulsations in the Sun (helioseismology) have revealed a wealth of detail concerning the Sun's internal structure and dynamics. Observations of pulsations on other Sun-like stars would extend our understanding of stars in general, and in particular would permit more exhaustive tests of stellar evolution theories than previously possible. CCD ensemble photometry at visible wavelengths provides one of

the most promising techniques for measuring such pulsations, but the expected pulsation amplitudes for Sun-like stars are small (only about three micro-magnitudes), while the best ground-based observations (conducted with a network of 4 meter-class telescopes) produce detection limits about 5 times as large.

Ground-based photometry is limited in precision by scintillation noise, which arises mostly in the troposphere. Simple scaling of ground-based scintillation noise to SOFIA, ignoring the lower turbulence amplitude in the stratosphere, indicates that the signal-to-scintillation noise ratio will be at least a factor of 3 lower than for a 10 meter ground-based telescope. This noise level would permit detection of solar-like pulsations within about 3 hours of observing time from SOFIA on any of about 300 stars. Rough amplitude estimates alone would significantly probe the mechanisms that excite and damp oscillations in stars like the Sun. For suitable stars (G and K dwarfs brighter than roughly 6th magnitude), observing the same star for 2 hours at the beginning and end of a 7.5-hour flight would allow resolution of the so-called "large frequency separation" in the stellar frequency spectrum, which immediately yields a precise estimate of the mean stellar density. Observations of one star over several nights could provide accurate frequency estimates for up to a dozen pulsation modes. Thus SOFIA will enable a significant program of stellar seismology.

(viii) Reprocessing of the ISM

The bulk of the elements heavier than helium have been synthesized in dying stars. These stars have finished the hydrogen burning phase in their cores and have commenced burning helium to form heavier elements. The central material is then mixed to the surface and is observable in the infrared in the form of bands of molecules, such as CN and CO, in the stellar spectrum. As the star evolves, these surface elements can be ejected back into the ISM by stellar winds, as in the case of the red giants, or in some cases by the loss of the star's whole outer shell, either at a non-catastrophic rate, as in the case of a planetary nebula, or at an explosive rate, as in the case of a supernova. In supernovae considerable nucleosynthesis of heavy elements can occur in the blast; for example observations from the KAO detected lines from nickel, cobalt, and iron atoms produced by the explosion of Supernova 1987A. The KAO also detected the formation of dust in the ejecta about 600 days after the explosion. SOFIA's sensitivity and resolution would permit improved studies of bright supernovae in other galaxies. Also, SOFIA will be well suited to study the common mass-loss stars such as the red giants and planetary nebulae, with sufficient sensitivity to permit resolution of the spectral lines of many important atoms and molecules, permitting studies of both the dynamics and rates of mass-loss.

(ix) Other Galaxies

Observations from the KAO discovered that spiral galaxies typically emit as much energy at far-infrared wavelengths as they do throughout the visible and ultraviolet. The extensive IRAS observations of galaxies showed that many have infrared luminosities exceeding their visible luminosities by factors of ten or more. ISO and SIRTf are anticipated to make great contributions

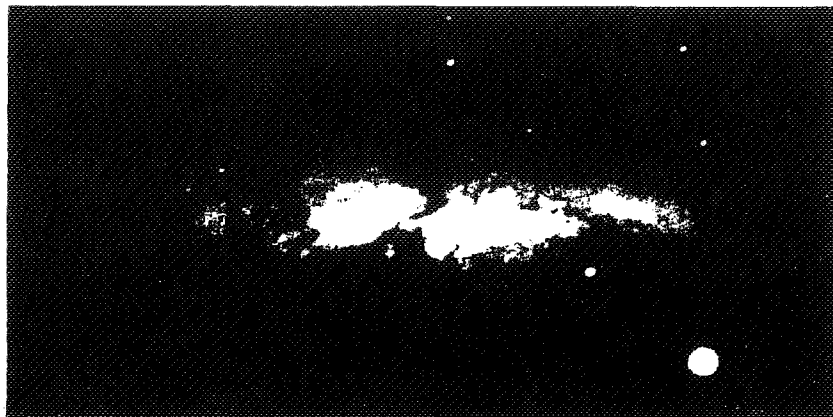


Figure 10. Optical photograph of M82.

to the understanding of other galaxies, but the high spatial resolution and the anticipated development of large far-infrared arrays enable SOFIA to make an important complementary contribution as well. SOFIA will observe nearby (~ 1 Mpc) spiral and irregular galaxies, nearby (~ 10 Mpc) starburst and Seyfert galaxies, and nearby (~ 100 Mpc) extremely luminous galaxies such as Arp 220 and Mrk 231. In the nearby spirals and irregulars, SOFIA's FIR arrays will investigate galactic structure and its influence on star formation at scales ~ 10 pc, primarily by mapping dust continuum and fine structure lines from atomic and ionized gas. At these scales, the relative positions and velocities of the molecular gas, dense photodissociated gas and H II regions, diffuse HI gas, dust IR continuum and the optical images of star forming regions will probe the roles of bars and spiral density waves in controlling star formation. Pressures in the neutral and ionized gas can be determined and correlated with star formation. Elemental abundance gradients can be measured as functions of galactocentric radius to constrain the past history of star formation and nucleosynthesis.

In nearby starbursts and Seyferts, SOFIA's ~ 100 pc resolution will map the star formation activity in the central kpc and may spatially separate the central interstellar medium affected by an AGN from the more extended region affected primarily by the ultraviolet radiation and shock waves induced by star formation and supernovae. NGC 1068 is an important example of a nearby Seyfert in which SOFIA will separate these two regions. M82 is a nearby starburst galaxy in which SOFIA will help unravel the nature of the central starburst. KAO measurements of O III (52 and 88 μm), N II (57 μm), O I (63 μm) and Si II (35 μm) line profiles from the obscured nucleus of M82 are consistently asymmetric and suggest strong variation in the emission from different components of the source. These components may be areas of intensive localized star formation, or recent supernova outbursts; supernovae are thought to occur in M82 every few years. Judging from radio maps, SOFIA could readily isolate some of the candidate components, but telescopes the size of the KAO and smaller ($\lesssim 90$ cm) cannot. The disturbed visible appearance of M82 (Figure 10) gives only a hint of the recent formation and violent demise of massive stars there.

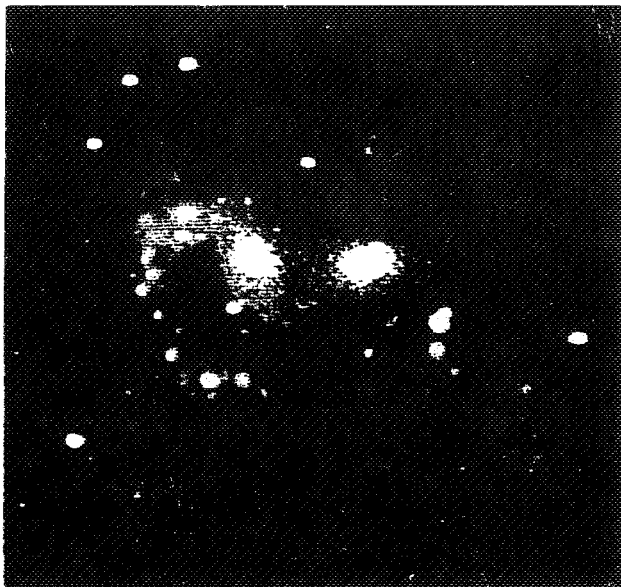


Figure 11. CCD image of the galaxy pair NGC 7318.

Many of the galaxies found to have large infrared excesses by IRAS have subsequently been identified as galaxies in collision. Study of these ultraluminous infrared mergers is seriously hindered at near-infrared, optical, and ultraviolet wavelengths because of the large obscuration by dust embedded in them. However, SOFIA will permit FIR, photometric, and spectroscopic imaging on a scale of ~ 1 kpc, adequate to reveal brightness distributions of emitting dust and gas on a scale comparable to the visible structure seen in many of these systems, and ample to distinguish components such as the active nuclei, the young starburst (O and B stars), the older starburst (SNRs, red supergiants), the shocked clouds, and the old stellar population.

Figure 11 shows the interacting galaxy pair NGC 7318 in Stephan's Quintet. In this false color image, which is a superposition of two optical CCD images taken through different filters, one can distinguish the older generation of stars that make up the bulk of the galaxies from the distribution of ionized hydrogen gas, which traces sites of recent star formation activity within the galaxies. The nuclei of the two galaxies are separated by 20 arcseconds.

Images at different wavelengths, including those beyond $100\ \mu\text{m}$ which IRAS did not sample, will yield temperature and optical depth profiles. Far-infrared and sub-millimeter spectroscopy will probe the excitation conditions, temperature, density, composition, and dynamics of the gas in these systems with similar spatial resolution. Far infrared rotational CO lines, and fine structure lines of O I, Si II, C II, O III, S III, and N III, will be important diagnostics.

(x) The Galactic Center

In many ways, the most exciting place in our own Galaxy is at its center where the stellar densities are very high, stellar collisions are probably frequent, and the existence of a central, massive black hole not unlikely. This region represents the closest galactic nucleus to us. Far-infrared observations have shown that the Galactic Center has an infrared luminosity of roughly $10^7 L_{\odot}$, is enshrouded in a dense dust ring, is to some degree shaped by magnetic fields, and is obscured at visible wavelengths by the intervening dust in the galactic plane by a factor of roughly 10^{10} . The distribution of red stars can be studied (with large extinction corrections) in the near-infrared and the distribution of ionized gas can be studied at radio wavelengths. However, the neutral atomic gas, thermally emitting dust, and important characteristics of the ionized gas can best be studied at the wavelengths accessible from SOFIA.

The ring of dust emission about the galactic center, which was first discovered from the KAO, is about 3 arcminutes in diameter and the cavity it defines at the center is only 30 arcseconds in diameter. Current results show that material from the ring (or outside it) may be spiraling into the center, that high turbulent velocities are present, and that magnetic fields may be important in this region. The data are consistent with the existence of a massive central object, possibly a black hole, or a compact cluster of stars. The exact location and character of the dominant source of luminosity in the cavity is unknown; two possibilities are the emission from a black hole accretion disk or emission from a number of massive stars. Of all the candidates for a massive black hole, if it exists, the non-thermal point source SgrA* is the most probable. Further, there is indirect evidence for the existence of a wind or jet originating at SgrA* causing a mini-cavity to be formed in the gas and dust about 5 arcsec southeast of SgrA*.

SOFIA will clarify the picture within the cavity on three times finer spatial scales than possible with the KAO, by resolving regions of different velocities, ionization levels, magnetic field directions (i.e. polarizations), temperatures, and gas densities. For example, a more accurate estimate of the location, UV spectrum, and luminosity of the central powerhouse within the cavity would be obtained by SOFIA by mapping the distribution of dust, neutral atomic and ionized atomic emission within the cavity with a three-fold improvement in spatial resolution over that achievable on the KAO. SOFIA could also study the jet (or wind) originating from SgrA* by measuring the fine structure line emission from the mini-cavity which is 4 arcsec in diameter. Line dilution makes this study impossible from the KAO. In addition, SOFIA could address the puzzle of where the massive stars in the cavity originate, if they are the source of the luminosity. The main sequence lifetimes for such stars are too short for the stars to form farther out and then diffuse into the central cavity. There is no evidence for dense molecular gas in the cavity but SOFIA may show the existence of neutral atomic clumps, perhaps characterized by high velocities, that cannot be spatially resolved by the KAO.

SOFIA, with its superior FIR resolution, would reveal if the streamer of neutral atomic gas inside the cavity is spiraling into the center from the inner surface of the dust ring or from outside the ring, possibly from clouds tens of parsecs away. Using FIR polarimetry, SOFIA will also image the structure of the magnetic fields within the dust ring and the cavity at a resolution that

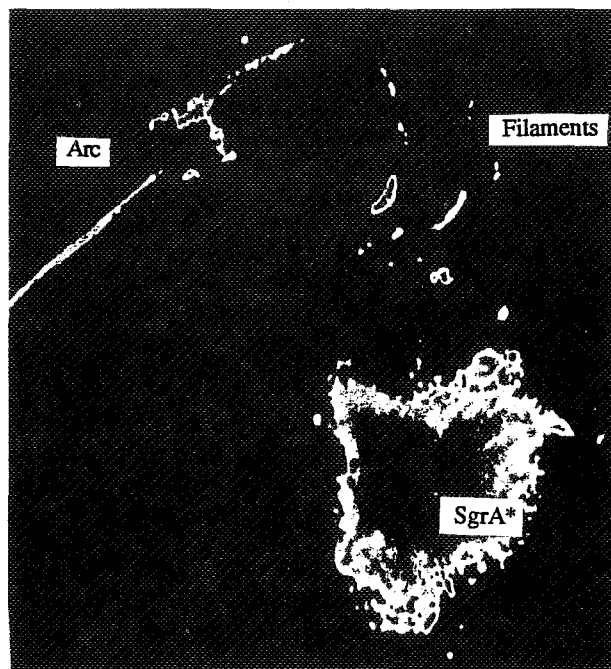


Figure 12. A grayscale radio (20 cm) image of the Galactic Center region. The figure is roughly 30 pc \times 30 pc or $\sim 15 \times 15$ arcmin in extent.

will be sufficient to test whether the dust ring is a magnetic accretion disk, removing its angular momentum centrifugally, or an assembly of unresolved magnetic streamers, or some other scenario.

Magnetic fields play an extensive role at larger scales in the vicinity of the Galactic Center as well. Ten arcminutes north of the dust ring, radio maps have shown the existence of peculiar large arcs of synchrotron emission, extending for about 20 pc perpendicular to the Galactic plane. The source of the electron excitation is unknown. These arcs seem, in projection, joined to the dust ring region of the Galactic Center via thermal arched filaments of ionized and neutral gas, and dust (see Figure 12). The KAO has shown that these filaments have luminosities $\sim 10^7 L_{\odot}$, and that the magnetic fields lie along the filaments, almost parallel to the Galactic plane. The source of ionization and heating of the arched filaments is also unknown, although undetected hot stars are the most likely candidate. However, the morphology of the filaments and the connection between the magnetic fields and such stars is a mystery. With the improved resolution of SOFIA we can use FIR fine-structure lines to examine ionization stratification in the arched filaments to seek the hypothetical embedded clumps of stars if they exist.

Obviously SOFIA will clarify our currently limited perception of phenomena in and around our own Galactic Center, which in turn will be a crucial step toward understanding similar phenomena seen on larger scales in many other galactic nuclei.

4. Comparison with Other Missions

Many important problems in modern astronomy require infrared observations with high sensitivity, high spectral resolution, and high angular resolution, or a combination of these capabilities. To fill these needs, the National Academy of Sciences Decade Survey (Bahcall) Committee has recommended *both* SOFIA and SIRTf (the Space Infrared Telescope Facility) as high priorities for development by NASA during the 1990's. A discussion and individual mission summaries of past and future infrared missions is contained in Session Nine of these proceedings, starting with the discussion summary by Caroff (1994).

Here we present a brief comparison of the principal missions SOFIA, SIRTf, ISO (the Infrared Space Observatory), KAO, and IRAS. Figure 13 and Table 3 depict the features of these missions which underlie the differences in their science goals. Table 3 compares launch/first flight dates, telescope diameters, design lifetimes, instrument complements, mobilities, and sponsors.

Table 3

KAO	IRAS	ISO	SOFIA	SIRTf
1974	1983	1995	2000	2002
0.91 meter	0.60 meter	0.60 meter	2.5 meter	0.85 meter
20+ years	1 year	1½ year	20 years	2½ years
12/Evolving	2/Fixed	4/Fixed	15/Evolving	3/Fixed
Deployable	Earth Orbit	Earth Orbit	Deployable	Solar Orbit
USA	USA+NED+UK	ESA+JPN+USA	USA+FRG	USA

Basically, the cryogenically cooled space missions achieve far higher sensitivity in broad wavelength bands, whereas the airborne facilities permit higher angular resolution and capacity to accommodate new instruments and science programs over a long lifetime. For example, the SOFIA science program will capitalize on its spatial and spectral resolution, for example in revealing how stars form, and on its mobility, which permits optimum observations of ephemeral events such as occultations. The SIRTf science goals exploit its excellent sensitivity and large detector arrays, for example to study galaxy formation at the edge of the visible Universe. SOFIA's targets will typically be galactic objects or nearby galaxies that may be studied in detail not possible with SIRTf, while many of SIRTf's targets will be faint or distant objects that would be undetectable with SOFIA. SIRTf's focal plane instruments are optimized for the highest priority scientific goals, but will be used for a range of scientific investigations. SOFIA's program is broad in scope because of its wide wavelength coverage, long lifetime, and annual opportunities to propose new science investigations and focal plane instruments.

As pointed out by Caroff (1994), in addition to its unique science potential, the airborne program provides unique continuity, training opportunities, and wavelength coverage to the infrared community.

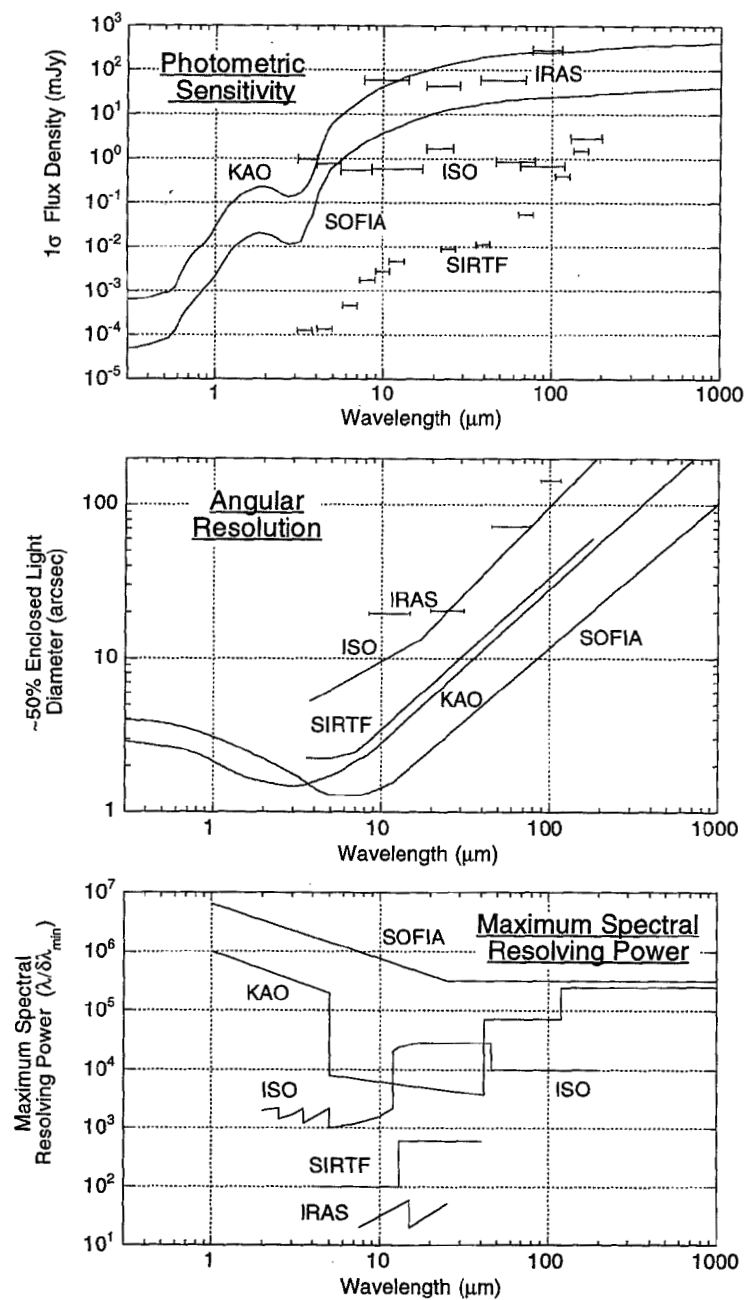


Figure 13. Photometric sensitivity, angular resolution, and spectroscopic resolving power for the KAO, IRAS, ISO, SOFIA, and SIRTf as a function of wavelength.

5. Education

Scientific and technical literacy are among the most critical needs of our nation. We benefit not only from brilliant researchers and creative inventors, but also from understanding of and respect for scientific endeavors by the taxpayers who must support them, and who themselves will be working in an increasingly scientifically and technologically advanced world. Thus, education in the fields of science, mathematics, and technology is not simply an investment in future scientists and engineers, but an investment in the appreciation of society for these endeavors. Through its unique scientific mission, SOFIA can increase this appreciation.

For scientists, SOFIA will provide a unique window to view the invisible infrared universe. However, for educators, it will be an exciting and accessible example of leading-edge high technology in the telescope, the scientific instrumentation, and the mission operations systems. For the public, SOFIA will serve as a high visibility, modern scientific facility, *epitomizing* the American ideals of innovation, exploration, and achievement.

The extensive participation in SOFIA observations by the science community, and the opportunities for teachers and the media to experience science in action on board, guarantee the potential of SOFIA for education. The rapid response of an airborne observatory to ephemeral astronomical events also helps to attract and focus public attention on science, as was the case for the KAO observations of Supernova 1987A, and for the impact of Comet Shumaker-Levy on Jupiter in 1994. These events frequently require remote deployments, which will expose this modern flagship of astronomy to the public world-wide, amplifying its effectiveness in expanding awareness of science.

The education program on SOFIA will offer to non-scientists a first-hand view of scientific research: its excitement, hardships, challenges, frustrations, teamwork, and discoveries. The intent of the SOFIA educational program is to bring these experiences to American students, teachers and the public routinely and on a significant scale. These outreach efforts will be built into the core program and evolve from the experiences with programs currently conducted with the KAO, such as the Flight Opportunities for Science Teacher EnRichment (FOSTER). SOFIA will be larger and fly more frequently than the KAO, and thus can support an expanded program.

Outreach activities are planned which will serve (1) pre-college students and teachers, (2) undergraduate and graduate students and faculty, and (3) the public and the media. SOFIA will promote excellence in science, mathematics and technology education through direct involvement of non-scientists with the SOFIA investigators, and via workshops, internships, and utilization of existing educational infrastructure such as museums and planetaria. In addition, many people will be able to experience SOFIA research remotely through the Internet and telepresence. Ongoing internal and external evaluation of the program will assure its effectiveness, much as the peer review process will do for the science program. Educational activities on SOFIA will touch the spirit and imagination of many American youth.

6. Technology

The unique observing potential, 20 year lifetime, and frequent opportunities for participation which SOFIA will offer the scientific community assure the development and prompt application of new technologies. Many of these will surely be valuable in future space and ground-based astronomy, as well as in other areas. The history of the airborne astronomy program is a guide to this process: the chopping secondary mirror, a feature of all modern infrared telescopes, was initially developed for the Learjet telescope. This facility also allowed the first "hands-on" testing of far-infrared bolometer detectors and a He³ refrigerator in an astronomical application.

KAO investigators have extended this work by making significant contributions to bolometer array and newer refrigerator technologies, which are used on ground-based submillimeter telescopes, as well as on the KAO. Detectors anticipated for use on SIRTf and AXAF are currently being flown in KAO instruments. Experience with KAO focal plane instruments has been applied to the design of the space missions IRAS, COBE, ISO, SWAS, Cassini, AXAF, WIRE, and SIRTf. Germanium photoconductor detectors developed for use on the KAO were actually used on IRAS. We anticipate that nearly all future space IR missions (*e.g.*, FIRST and Edison) will reap major benefits from SOFIA-related technology.

Some of the technologies evolved in conjunction with SOFIA may have commercial applications. For example on the KAO, extensive research was done to develop infrared radiometers to measure the atmospheric water column depth overhead; this technique proved useful in detecting clear air turbulence, and the technology is now under review for suitability on commercial aircraft. In conjunction with wind tunnel testing of the SOFIA model, a pressure sensitive paint has been developed to provide very high spatial resolution of the pressure variations on airfoils; this technology has already been applied by major American aircraft companies in new wing designs. Future SOFIA technology could find application in aerodynamic noise reduction for aircraft, automated intelligent systems monitoring of real-time control systems, and mission operations and planning procedures for space flight.

7. Readiness

A configuration with the telescope cavity located behind the wing has been shown in predevelopment studies with aircraft modifiers to be much less expensive than putting the telescope ahead of the wing. Extensive analysis, including infrared observations of the exhaust plumes from NASA's Shuttle Carrier Aircraft (a Boeing 747), has shown that scattered emission from this source is not a concern for all but a very small class of possible science investigations. The aft configuration has been adopted as a cost cutting measure, although it may increase the seeing distortion of the images at near infrared wavelengths (Figure 2) due to the thicker boundary layer in the rear of the plane. Figure 14 depicts the design with the aft cavity installation of the telescope.

Wind tunnel tests of the airflow over the open-port telescope in an aft cavity have resulted in a quiet, low drag shear-layer control concept for SOFIA, and have demonstrated that the flow reattachment is stable and the control

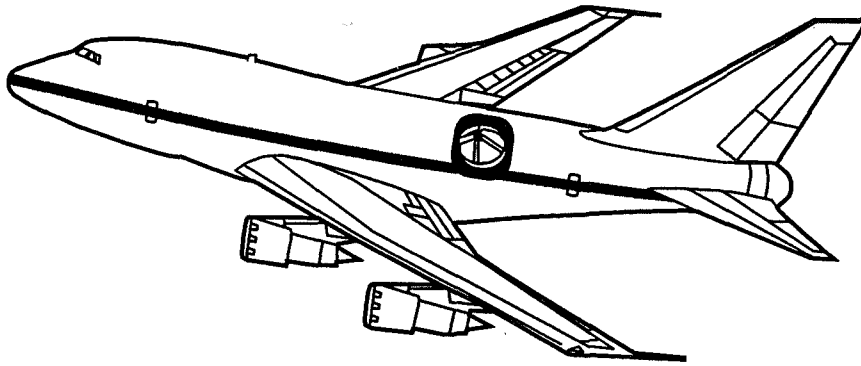


Figure 14. The baseline SOFIA design concept.

of the aircraft is not affected for expected flight conditions. These tests also provide good estimates of the wind loading on the telescope. Further wind tunnel tests are anticipated to select among the door design concepts currently being considered.

The telescope design (Figure 15) features an airbearing support and numerous other similarities to the KAO telescope, which has achieved sub-arcsecond pointing stability even in light turbulence. Structural and optical analyses indicate that either a metal or composite structure could be used, and that any of several (glass) primary mirror designs would work. The 2.5 m primary can be as slow as $\sim f/1.5$ with the telescope in the aft location, so that figuring is not a problem; the chopped image quality is better for larger primary f-numbers.

SOFIA definition studies, sponsored jointly by NASA and the German Space Agency DARA, have been completed, and the project has been deemed ready for development by these agencies. If funding is available, NASA and DARA plan to begin the development of SOFIA in 1996, which would permit the first flights to occur in the year 2000.

8. Conclusion

The characteristics of SOFIA – its astronomical promise, moderate cost, maintainability, and opportunities for broad-based community participation – will extend the tradition of the airborne program for innovation, education, and exciting science. Its vision will penetrate dark reaches of our own and other galaxies, revealing objects and processes otherwise hidden from view with spatial resolution which will be unmatched until well into the next century. It will elucidate problems ranging from the spectacular death of massive stars to the inconspicuous incubation of low mass stars, from the composition of interstellar dust to the formation of prebiotic materials and protoplanetary

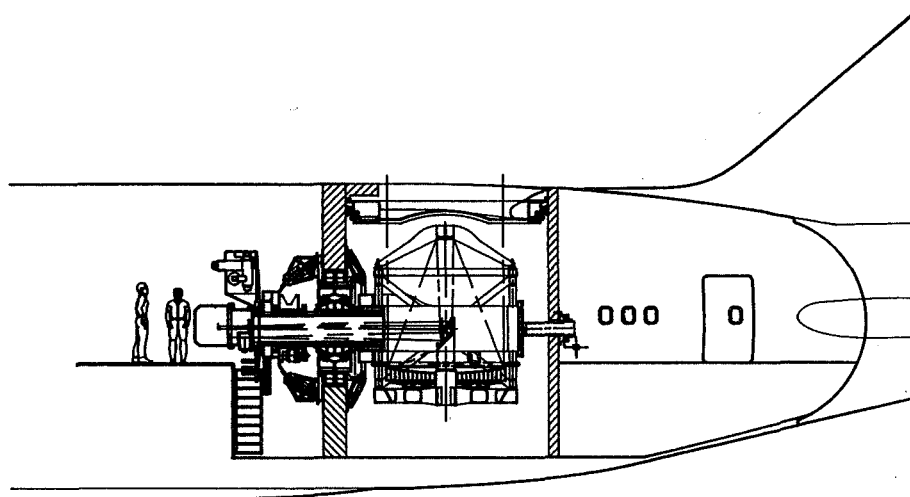


Figure 15. The SOFIA telescope installation in a Boeing 747-SP.

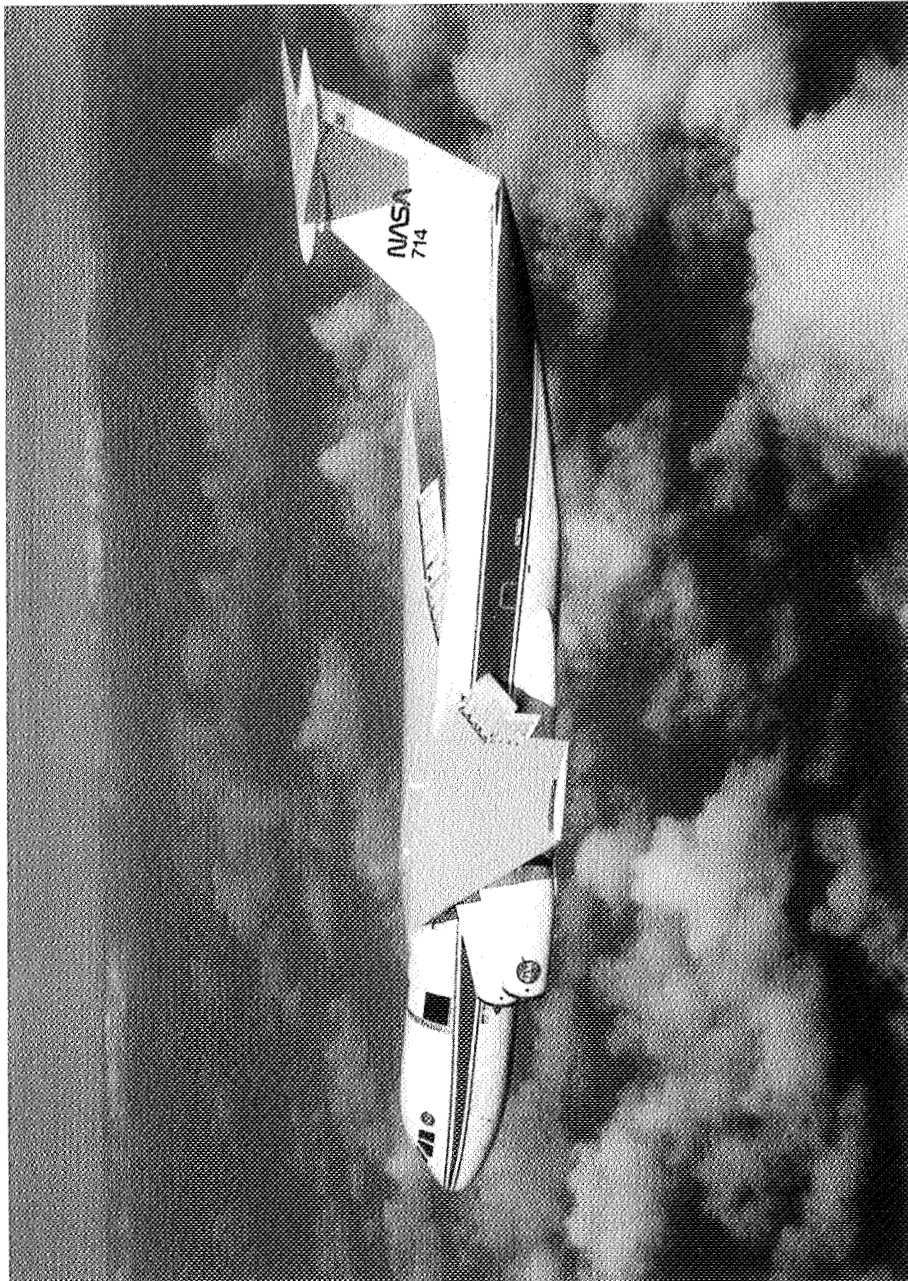
systems, and from the enigmatic character of our own Galactic Center to the nature of stupendous luminosity sources in colliding galaxies. SOFIA's image, performance, and accomplishments will be a credit to its heritage.

9. Acknowledgments

It is a pleasure to thank Al Betz, Harold Butner, Dale Cruikshank, Ted Dunham, David Hollenbach, and Dan Lester for contributions to the science section, Edna DeVore for contributions to the education section, and Mike Werner for assistance with the comparison of SOFIA to other missions. The photograph of M82 was provided by the Mount Wilson and Las Campanas Observatories, Carnegie Institution of Washington. The photograph of Beta Pictoris is credited to Bradford Smith (University of Arizona) and Richard Terrile (JPL). The picture of Uranus and its ring system was painted by Rick Sternbach. Howard Bushouse (Computer Sciences Corporation) provided the CCD image of NGC 7318. The drawings SOFIA and of the SOFIA telescope were produced by Dan Machak and Will Valloton (respectively) of NASA Ames.

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